Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 999 (1997)

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DOI: https://doi.org/10.5169/seals-1039

Pseudodynamic Tests of Partially Concrete-Filled Steel Bridge Pier Models

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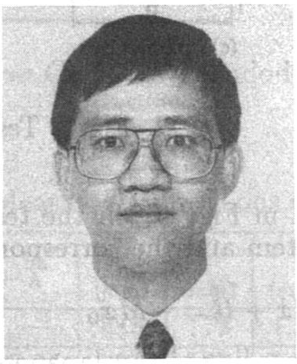

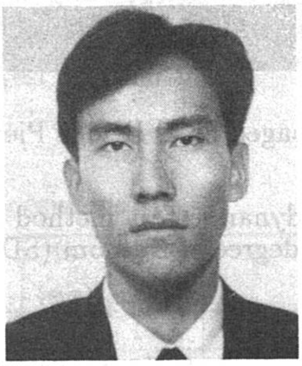

Summary

In the present paper, experimental results of concrete-filled steel box columns under dynamic loading are reported. To investigate the dynamic behavior of concrete-filled steel box columns, three specimens with different natural periods were tested using the pseudodynamic test method. For comparison, a hollow steel column specimen with the same dimension was also tested. Test results showed that concrete-filled steel box columns can be effectively used as bridge substructures to withstand severe earthquakes.

1. Introduction

Use of steel bridge piers becomes more and more popular especially in Japan. Steel bridge piers are normally designed as cantilever columns or planar rigid frames with thin-walled box or pipe sections. However, severe damage and even total collapse of such piers was observed during the Hyogoken-nanbu Earthquake on January 17, 1995. One such pier is shown in Fig. 1 where local buckling can be seen near the base. This shows the insufficient ductility capacity of the steel bridge piers to the strong earthquakes.

In order to study the seismic behavior of steel box columns and concrete-filled steel box columns under cyclic and dynamic loading, a large number of tests[1~3] have been carried out at Nagoya University since 1989. These studies produced a lot of valuable information in developing rational earthquake-resistant ultimate-strength design methods for such bridge piers.

2. Outline of Pseudodynamic Tests

In this study, test specimens used are of box sections with with one or two stiffeners on each flange plate and one stiffener on each web plate (see Fig. 2). A conceptual flow of

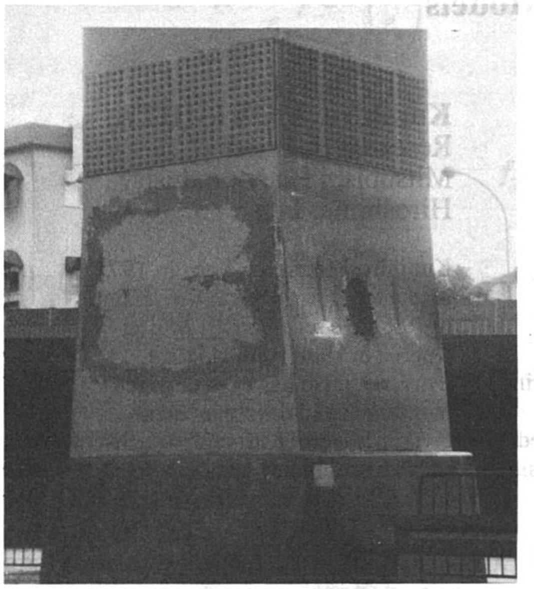

Fig. 1 Damaged Steel Bridge Pier

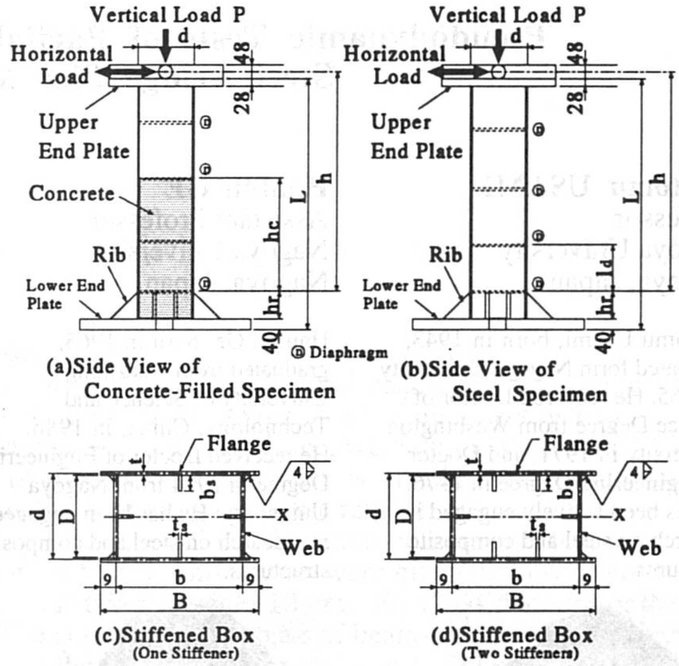

Fig. 2 Test Specimens

the pseudodynamic test method is shown in Fig. 3. In the test the specimen is modeled as a single-degree-of-freedom (SDOF) system and the corresponding equation of motion is solved.

$$M\ddot{x} + C\dot{x} + R = -M\ddot{x}_0 \tag{1}$$

The mass M of the system is calculated according to the Japanese Road Association code[4] in which the weight of a superstructure and 80 % of the weight of the bridge pier are considered. The damping coefficient C is then obtained from the mass and stiffness K with a value of 0.05 for the damping factor ξ. The ground motion accelerogram $\ddot{x}_0$ is specified in the form of a digitized record for each time step. In each step, a specified displacement is quasi-statically applied to the specimen, and the corresponding restoring force R induced is measured and used to compute the displacement to be imposed in the next step. The equation of motion is solved using an explicit integration method.

Although many factors may affect the seismic response of the bridge pier, discussion will now be limited to the effects of the filled-in concrete and natural period. For this purpose, one steel specimen and three concrete-filled steel specimens are designed and tested as cantilever type of columns fixed at the base. A scale factor of $S = 8$ was used in fabricating the specimens.[5] The measured dimensions of the specimens are given in Table 1. In the table, R_f and $\overline{\lambda}$ are flange width-thickness ratio parameter and column slenderness ratio parameter, respectively, and defined by

$$R_f = \frac{b}{nt}\sqrt{\frac{12(1-\nu^2)}{\pi^2 k}}\sqrt{\frac{\sigma_y}{E}}\ , \qquad \overline{\lambda} = \frac{Kh}{r}\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}} \tag{2,3}$$

in which b = flange width; t = plate thickness; n = number of panels of a flange; σ_y = yield stress; E = Young's modulus; ν = Poisson's ratio; k = buckling coefficient of plate panel = 4.0; h = column height; K = effective length factor (= 2.0 for a fixed-free column); and r = radius of gyration of steel section.

From the tension tests of three coupons, average material properties of steel are determined and shown in Table 2. The average material properties of concrete are f_c = 19.4 MPa, E_c = 22.3 and μ = 0.162. The length of filled-in concrete determined is based on an optimum length concept used in a previous study.[6] The optimum length of filled-in concrete is such

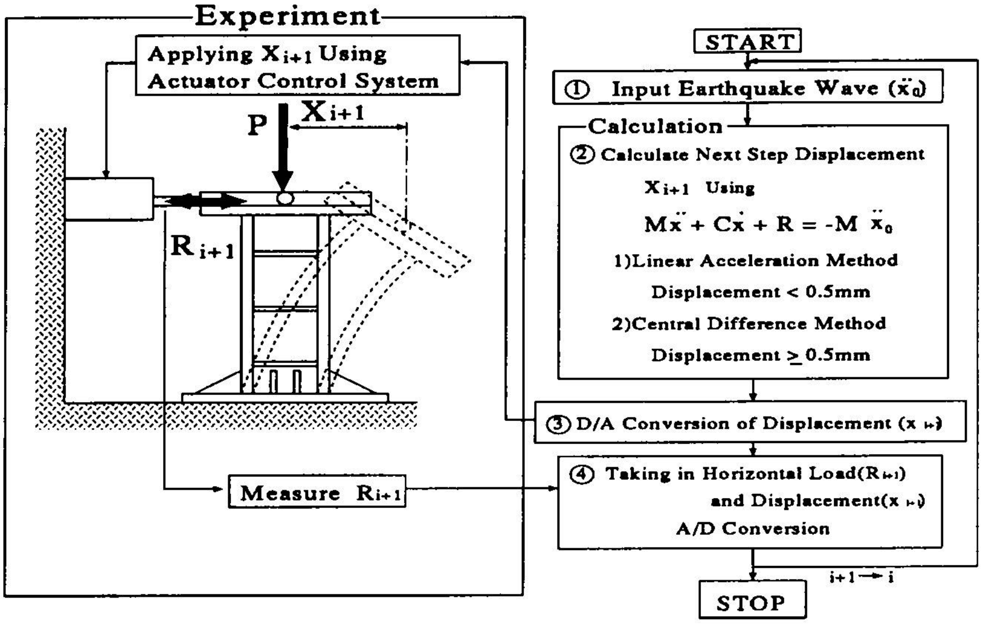

Fig. 3 A Flow Chart for Pseudodynamic Test Method

Table 1 Measured Dimensions of Test Specimens

Specimen	L (mm)	h (mm)	$\frac{h_c}{h}$	B (mm)	D (mm)	t (mm)	bs (mm)	ts (mm)	γ/γ^*	$\bar{\lambda}$	R_f
S45-35H	1153	973	—	285	172	4.31	42	4.31	14.1	0.380	0.480
SC45-25-25H	1051	904	0.25	321	197	5.00	43	5.00	2.4	0.262	0.404
SC45-35-20H	1449	1265	0.20	321	197	4.71	43	4.71	2.7	0.374	0.436
SC45-60-20H	1653	1434	0.20	220	130	5.05	30	5.05	2.3	0.619	0.400

Note: γ = relative flexural rigidity of one stiffener;
γ^* = Optimum value of γ obtained from linear buckling theory;
For other notations, refer to Fig. 2.

a value that makes both the hollow steel section and concrete-filled steel section near the column base reach simultaneously failure. At this state, the ductility of the column will be highest.

Table 2 Material Properties of Steel

Specimen	σ_y (MPa)	E (GPa)	ν
S45-35H	374	192	0.277
SC45-25-25H	295	208	0.266
SC45-35-20H	303	207	0.263
SC45-60-20H	295	208	0.266

The axial loads used in the tests were calculated based on the expected horizontal force given by the seismic coefficient of the Japan Road Association code[4] and the interaction equations proposed by Usami.[7] The calculated values of the axial loads for the specimens are shown in Table 3.

Three earthquake accelerograms (JMA, JR-Takatori and Higashi-Kobe) recorded during the Hyogoken-nanbu Earthquake of January 17, 1995 were used. The accelerograms are shown in Fig. 4 and it should be noted that the records JMA, JR-Takatori and Higashi-Kobe were

Table 3 Input Values of Pseudodynamic Tests

Specimen	Ground Type	$\frac{P}{P_y}$	M $kN \cdot s^2/mm$	K kN/mm	C $kN \cdot s/mm$	T sec	$\frac{\delta_R}{\delta_y}$	$\frac{\delta_{max}}{\delta_y}$	$\frac{H_{max}}{H_y}$
S45-35H	III	0.143	1.841	117.22	1.551	0.764	1.22	3.30	1.55
	I	0.199	2.551	117.22	1.825	0.899	1.77	3.75	1.78
	II	0.167	2.139	110.81	1.620	0.873	5.34	10.61	1.70
SC45-25-25H	III	0.172	2.148	327.03	2.650	0.509	0.10	2.40	1.52
	I	0.235	2.931	289.06	2.911	0.635	2.18	9.52	2.24
	II	0.199	2.479	267.70	2.576	0.605	1.43	10.12	2.24
SC45-35-20H	III	0.130	1.561	108.95	1.304	0.752	0.90	3.42	1.80
	I	0.182	2.177	99.46	1.471	0.929	1.17	4.44	1.94
	II	0.152	1.818	98.92	1.341	0.852	2.63	9.75	2.03
SC45-60-20H	III	0.081	0.655	23.19	0.390	1.056	0.89	3.03	1.49
	I	0.129	1.036	21.97	0.477	1.365	0.38	2.78	1.64
	II	0.096	0.770	20.75	0.399	1.211	0.44	5.43	1.79

obtained respectively from Ground Types I, II and III. Here, ground Types I, II and III correspond to hard (rock), medium and soft soil sites, respectively. The specimens were repeatedly subjected to these accelerograms in the order of Higashi-Kobe, JMA and JR-Takatori.

In Table 3, the values of the mass M, stiffness K, damping coefficient C and natural period T for converted real bridge piers ($S = 8$) are summarized. The natural period of each specimen, T, is computed as

$$T = 2\pi\sqrt{\frac{M}{K}} \qquad (4)1$$

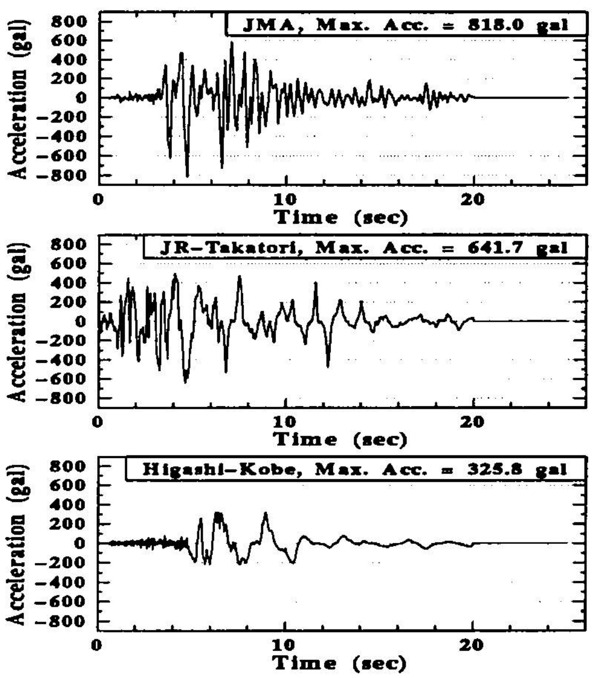

Fig. 4 Input Earthquake Accelerograms

3. Experimental Results

To investigate the effect of filled-in concrete on the seismic response of steel box columns, a steel specimen S45-35H and a concrete-filled steel specimen SC45-35-20H are considered here. As indicated previously, for the specimen SC45-35-20H, the length of filled-in concrete is determined as $0.2h$ based on the optimum length concept.

Fig. 5 shows horizontal displacement-time history and horizontal load-horizontal displacement curves obtained from the tests of the two specimens subjected to JR-Takatori accelerogram. The comparison shows the difference in the displacement response and restoring force. The measured residual displacement δ_R after the test and maximum displacement response δ_{max} during the test for each input accelerogram are summarized in Table 3. As can be seen from Fig. 5 and Table 3, the maximum response displacements δ_{max}/δ_y are almost the same but the residual displacement δ_R/δ_y is significantly reduced by filling concrete inside. For both accerelograms of JR-Takatori and JMA, the residual displacement of the concrete-filled steel specimen SC45-35-20H is only about half of that of the hollow steel specimen S45-35H. Therefore, it can be concluded that the filled-in concrete is effective in improving the seismic behavior of steel columns. The damage appearance of the hollow steel specimen S45-35H after the test is shown in Fig. 6.

Three concrete-filled steel specimens are used herein to investigate the effect of the natural period on the seismic behavior of the columns. The specimens are of nearly the same values of R_f, but significantly different values of $\overline{\lambda}$. Thus, the natural periods of the specimens converted to real bridge piers with $S = 8$ are largely different. As an example, Fig. 7 shows time history responses and horizontal force versus horizontal displacement responses of the three specimens subjected to the JR-Takatori accelerogram. In the case of the specimen SC45-25-25H with a value of $T = 0.605$ second for the converted real bridge pier, the relatively large and sudden increase in the displacement occurred at about 5 seconds after the input of the ground acceleration was started (see Figs. 7(a) and 7(b)). At this moment, the nondimensionalized displacement δ/δ_y was as large as 10, and the structure was severely damaged. The subsequent cyclic displacements were still large and difficult to recover from the excessive drift. The natural period T of the real bridge pier converted from the specimen SC45-35-20H is 0.852 second and it is larger than that for the converted bridge pier of the specimen SC45-25-25H. In this case, the induced responses as shown in Figs. 7(c) and 7(d) were smaller than those of the specimen SC45-25-25H. For the third specimen SC45-60-20H, its responses were generally milder. As is seen in Figs. 7(e) and 7(f), the response displacement and dissipated energy were relatively small.

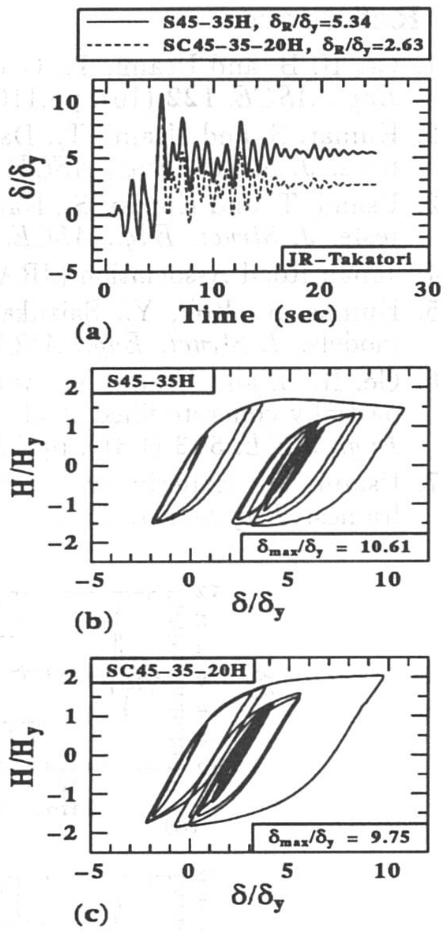

Fig. 5 Effect of h_c/h on Seismic Responses

The maximum response displacement (δ_{max}/δ_y) and residual displacement (δ_R/δ_y) of the three specimens are given in Table 3. Plots of δ_{max}/δ_y and δ_R/δ_y against the natural period T are shown in Fig. 8. Thus, it can be found that the responses of structures under earthquake loadings simulated using the JR-Takatori and JMA earthquake accelerograms are very sensitive to the natural period. In other words, these two earthquake accelerograms produce large responses when the structure's natural period is small, for example, $T < 1.0$.

4. Conclusions

Results of the pseudodynamic tests showed that the residual displacement of steel bridge pier can be significantly reduced by filling concrete inside, but the improvement of the maximum response displacement can not be expected. On the other hand, it is found that the natural period of the bridge piers has a large influence on the seismic responses.

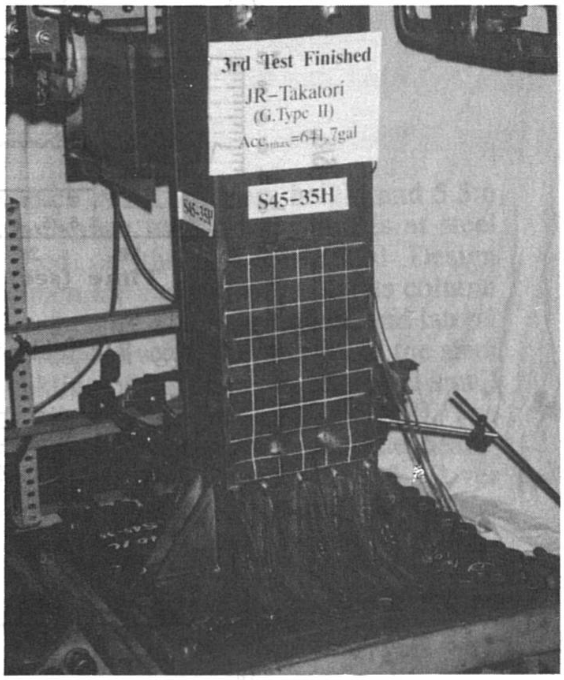

Fig. 6 Damaged Steel Column
(without concrete)

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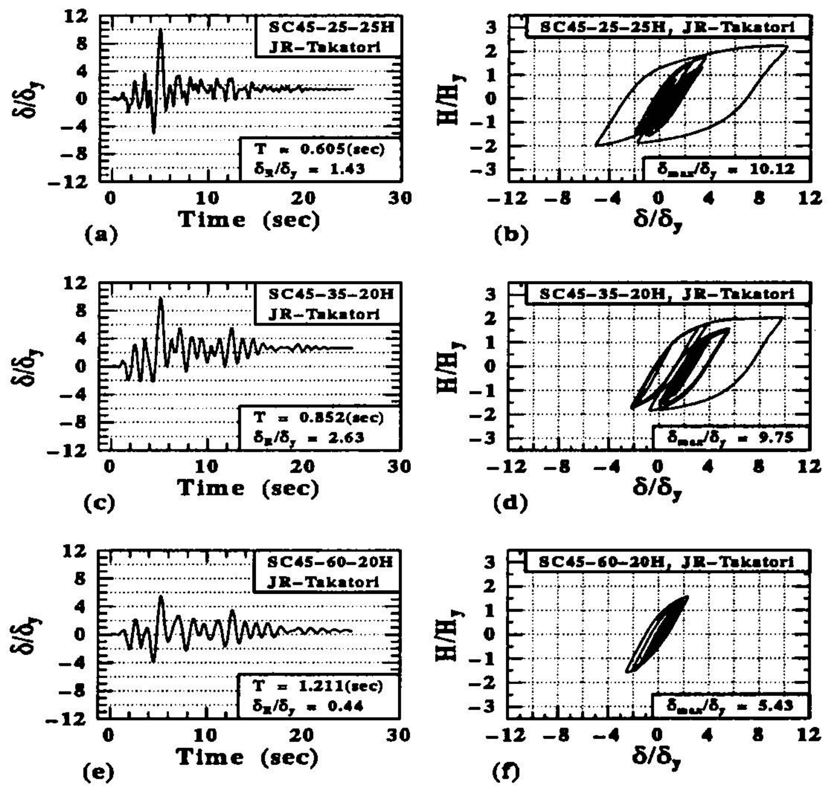

Fig. 7 Effect of T on Seismic Responses

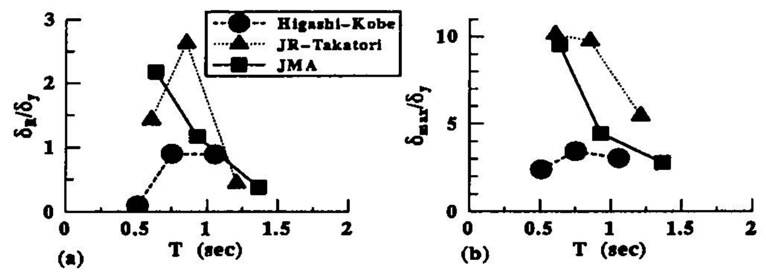

Fig. 8 Effect of T on δ_R/δ_y and δ_{max}/δ_y